Measured and Modeled High-Frequency Acoustic Impulse Responses in Very Shallow Water

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Abstract— **A goal of the Center for Island, Maritime, and Extreme Environment Security (CIMES) is to develop passive acoustic methods to monitor harbor and near-shore environments. Advantages of passive systems include source classification capabilities (since sound sources have different signatures), improved detection and tracking capabilities in cases when sonar avoidance and jamming technologies are used, the ability to monitor the environment without alerting the intruder, and minimal environmental impact for sensitive areas. Localization and tracking of targets relies on understanding the acoustic field properties and propagation characteristics. For this reason, a series of experiments were conducted to determine empirical impulse responses and to evaluate the performance of acoustic propagation models at high-frequencies (10-80kHz). The experiments were conducted on site of the CIMES passive acoustic system, which is near-shore in shallow (~10m) water off the south shore of Oahu, Hawaii. This paper presents the methods and results of these experiments and compares them with acoustic propagation model predictions. Implications for passive acoustic tracking are discussed.**

Keywords-underwater acoustics; surveillance; tracking; shallow water; high frequency; surface waves

I. INTRODUCTION

Passive acoustic surveillance refers to the detection and tracking of sound sources based on their sound output. Ability to track and detect sound sources depends on ability to predict and model sound propagation through the water column. Unfortunately, acoustic propagation in shallow coastal waters is notoriously difficult due to environmental complexity (including range-dependent bathymetry and sound speed profiles) and time-dependent variations (including surface and internal waves).

This paper presents the initial results of our first shallow-water acoustics experiment in the area where the CIMES (http://www.cimes.hawaii.edu/) cabled acoustic system will be deployed. This site is part of the Kilo Nalu Nearshore Observatory (Pawlak et al. 2009; http://www.soest.hawaii.edu/OE/KiloNalu/), which is located just offshore from the entrance to Kewalo Small Boat Harbor in Honolulu, Hawaii.

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II. EXPERIMENTAL MEASUREMENTS

Data were collected on August 27, 2010. The measurement set-up is shown in Figure 1. Equipment used was the same as that described by Fedenczuk et al. (2010). The transmitter was suspended off the back of an anchored buoy. Signals were received by a vertical array of 4 hydrophones suspended from the Research Vessel Alchemy, which was moored at three points to minimize motion. Elastic chords were used to decouple the transmitter and hydrophones from vessel motion on both the transmit and receive ends. GPS receivers aboard RV Alchemy and mounted to the buoy were used to measure source-receiver separation and movement during the experiment. Measurements were taken at 8 different positions with source-receiver distances that varied between 5 and 50m.

The bottom was an almost completely flat at ~7.9m depth limestone reef with patches or life reef and carbonate sands. A small south swell during the experiment resulted in conditions with unbroken surface waves of 9.7s dominant period and 0.75m significant wave height. Winds during the time of measurement were light at about 5 knots. Sound speed was measured with sound velocity profiler lowered from RV Alchemy; it was almost constant with depth at 1536 m/s.

Transmitted signals consisted of a sequence of tones, FM sweeps, and m-sequences. Source levels were kept very low (~90dB re. 1μPa) to eliminate any possibility of environmental impact. In post-processing, transmitted signals were cross-correlated with filtered received signals to obtain impulse responses.

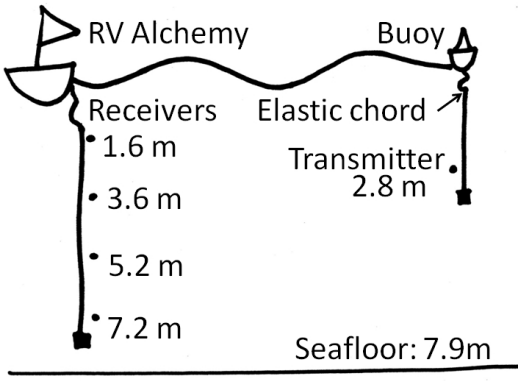


Figure 1. Experimental configuration.

III. RESULTS

Plotted in Figure 2 are the envelopes of 10 measured impulse responses at a range of 14.8 m for the 4 hydrophone depths. The solid curved lines correspond to the modeled direct and surface-reflected arrival times for a flat surface (no waves). Measured direct arrivals are steady and arrive as expected but measured surface reflections vary rapidly and significantly in arrival time, shape, and magnitude. Although many phenomena influence the propagation of high frequencies in shallow water, the dominant cause of the fluctuations observed in our data is the dynamic surface wave-field and wave focusing of surface-reflected signals. Indeed, surface wave focusing is an important phenomenon that results in highly transient and dynamic surface arrival patterns and that is well recognized in underwater acoustics literature (e.g. Williams 1994; Tindle 2002; Preisig and Deane 2004; Tindle and Deane 2005).

The spread in surface-reflected arrival times for a given depth can be understood by thinking of water depth changing as a wave passes overhead. While this change does not affect the direct arrival, surface-reflected rays will have a longer or shorter distance to travel depending on the wave phase. A time spread of about 0.5ms observed in Fig 2 for surface-reflected arrivals is reasonable given a wave-height of 0.75m.

To help explain the different shapes and amplitudes of the surface reflections, Figure 3 shows surface-reflected rays in a ray trace for a 2.8m source depth, 7.9m bottom depth, and sinusoidal surface with 60m wavelength and 0.75m peak-to-peak magnitude. The ray trace uses specular reflection at the point where the ray strikes the surface. Immediately evident is the convergence of a group of reflected rays at 45m range. Another way to illustrate this surface wave focusing effect is by using a depth-time diagram similar to the one shown in Figure 2. Figure 4 shows the time-depth diagram corresponding to the ray trace from Figure 3 at a range of 55m. The folding between depths of 5.2m and 6m is due to ray convergence. Drawing a line through a depth of 5.6m (inset) reveals 3 points of intersection, which correspond to arrival times of three different surface-reflected rays for that depth. This demonstrates how ray focusing can cause multiple surface-reflected arrivals at a given range and depth. The received signal, then, depends how the multiple reflections interact on arrival at the receiver. As the wave-field is dynamic, so are the reflections.

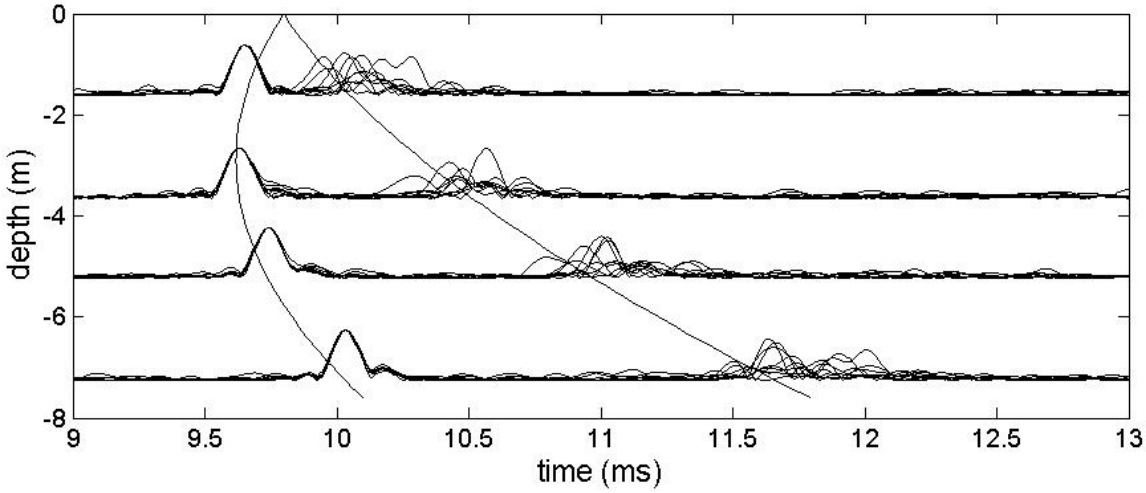


Figure 2. Envelopes of 10 measured impulse responses at 14.8 m range at the 4 hydrophone depths. The solid curved lines correspond to the modeled direct and surface-reflected arrival times with no surface waves.

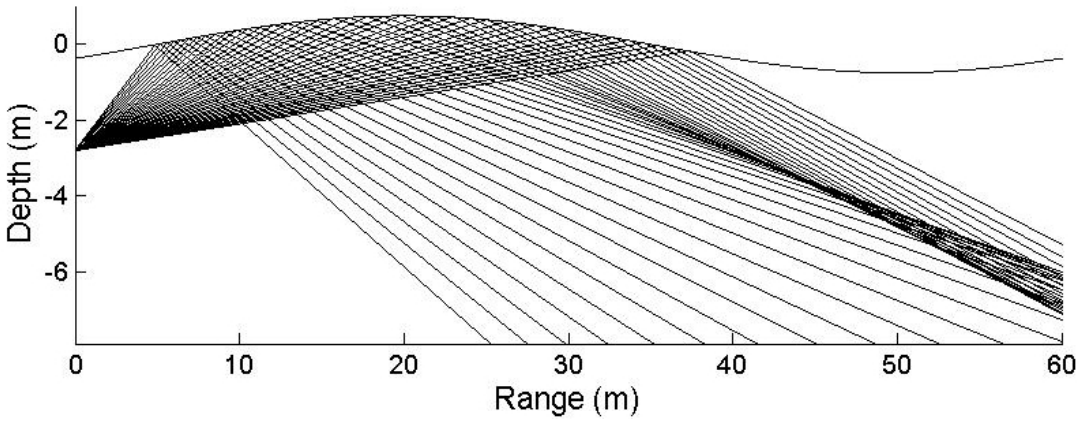


Figure 3. Ray trace for a 2.8m source depth, 7.9m bottom depth, and sinusoidal surface with 60m wavelength and 0.75 m peak-to-peak magnitude.

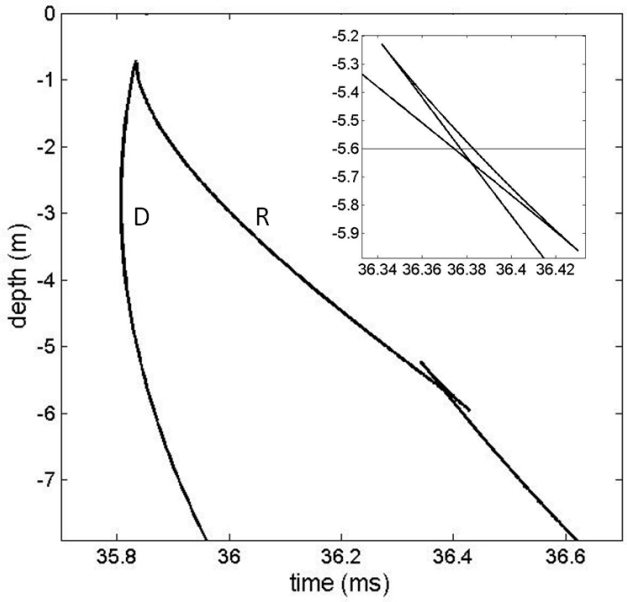


Figure 4. Depth-time diagram from ray trace in Fig 3 at 55m range. Direct (D) and surface-reflected branches (R) are as labeled. The inset is a blow-up of the folding region.

IV. DISCUSSION

At the distances considered here, direct arrivals were remarkably steady and predictable. Surface reflections, on the other hand, were highly variable due to the dynamic nature of the surface wave-field.

A more detailed analysis of the data presented in this paper is underway. For this experiment, however, precise modeling will not be possible for several reasons. The most important limitations to model precision are movement between sources and receivers and insufficient measurement of the surface wave-field. Future experiments will aim to resolve these problems in an effort to better understand shallow water propagation.

In most practical situations and applications, there is inevitably equipment motion and position uncertainty, and full environmental information (including wave-field measurements) is rarely available. It follows that passive acoustic methods for detecting and tracking underwater objects in shallow-water conditions must account for uncertainties and fluctuations in surface-reflected arrivals. Where less dynamic direct and bottom-reflected paths are available, it might be advantageous to use processing methods that attempt to eliminate surface-reflections, despite the potential information on source characteristics that they carry. Where dependence on surface-reflections cannot be minimized, statistical methods will be necessary to deal with the dynamic nature of acoustic propagation.

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